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THERMAL PROPERTIES OF LOOSE TUBE SECONDARY COATED OPTICAL FIBRES EXPERIMENTALLY DISCUSSED BY A RELATIVE LIGHT PULSE DELAY TECHNIQUE

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Abstract

For silicone primary coated optical fibres in loose tubes it is observed that the 150°C wide temperature interval of no excess loss can be much broader than the temperature interval where the fibre is stress free, and therefore it is most important to be able to control the latter of these intervals as well. The upper limit of this stress free temperature interval is precisely measured by a new interpretation of the temperature versus light propagation time curve, and for the first time it is reported that this upper limit can be controlled over a wide range in agreement with a simple model of the extrusion process. In addition, dynamical relaxation is observed and one result is a shrinkage as low as 0.35% after 160 hours exposure at 70°C. Loose tube fibres with silicone primary coating and polycarbonate secondary coating show excellent and stable optical and mechanical properties in a large temperature window.

Introduction

To assure long-term optical and mechanical stability of fibre optic cables operating at varying ambient conditions, it is of fundamental importance that the glass fibres are not exposed to external longitudinal stress in order to protect the fibres against static fatigue. Therefore, it is necessary to be able to carefully control the thermal properties of the secondary coated fibres.

One common way to apply the secondary coating to an optical fibre is to extrude a loose tube around the fibre. An optical fibre in a loose tube of a certain radius of curvature will only remain unperturbed in a limited temperature interval due to the difference in thermal expansion coefficient of the glass and plastic materials. These perturbations, occurring at low and high temperatures, might induce excess loss in the optical fibre due to bendings and micro-bendings. The observed excess loss depends strongly upon the hardness of the primary coating material. The temperature interval, where no excess loss is observed, can easily be determined experimentally and until now, it has been the practice to identify this interval with the temperature interval where the fibre is stress free.[1,2]

In this work, direct measurements of the upper limit of the stress free temperature interval have been performed by measuring as a function of temperature the change in time delay of short light pulses passing through the loose tube jacketed fibre. Bu such relative light pulse delay (RLPD) measurements, it has been found that this stress free temperature interval can be much narrower than the temperature interval of no excess loss. Further, it has been observed that in accordance with a simple model of the extrusion process the position of the stress free temperature interval can be accurately controlled by manipulating the extrusion conditions such as back tension force, cooling water temperature, and other extrusion parameters.

Finally, it has been shown that this measurement technique is most suitable to study dynamical relaxation phenomenons, for example, shrinkage of the extruded plastic tubes at elevated temperatures.

Measurement Procedure

The measurements were performed using the equipment shown in Fig. 1.[3] Short light pulses ($\lesssim$ 0.3 ns FWHM) are obtained from an 850 nm laser, and these pulses are divided in two parts in the Y-coupler; one passing through the fibre to be measured placed in temperature controlled environments, the other launched onto the avalanche photodiode through a short reference fibre. The high degree of stability of the 5 MHz external triggering oscillator assures that the relative time difference between the two pulses can be obtained accurately, the measuring time being 5-10 seconds, typically.

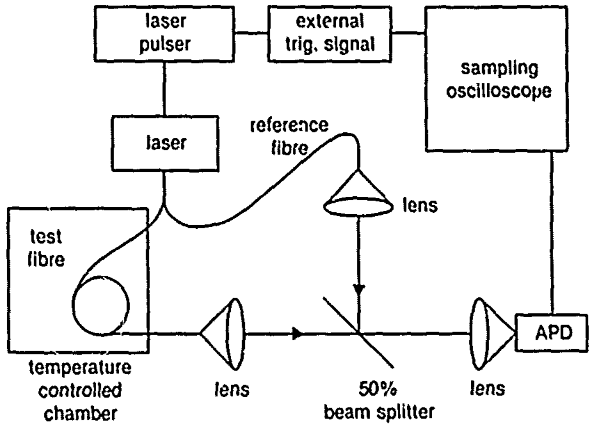

Figure 1. Schematic diagram of relative light pulse delay measurement experiment.

In general, variations in the surrounding physical conditions experienced by the optical fibre imply relative light pulse delay changes, and RLPD-data at different temperatures are related to the stress state of the fibre. However, it is necessary to take into account the dependence of the refractive index on temperature and stress in the evaluation of the data. In all the experiments, B_2O_3-P_2O_5-GeO_2 doped 0.20 NA multimode fibres were used, and in Fig. 2 the elongation versus light pulse delay change curve for that type of primary coated fibre is shown as obtained by our experiments.

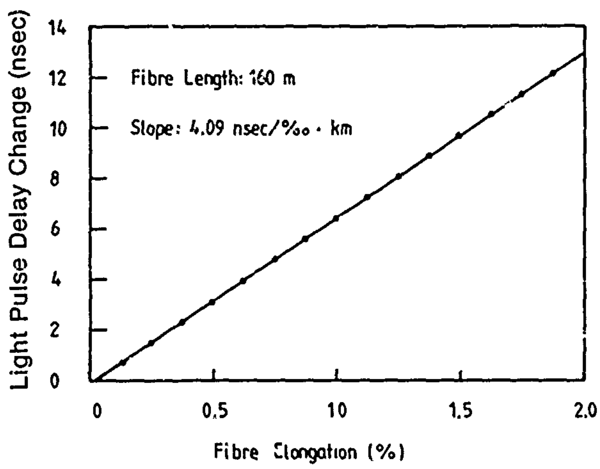

Fig. 2 Transmission time versus fibre elongation curve at 25°C for a B_2O_3-P_2O_5-GeO_2 doped 0.20 NA multimode fibre

The slope is 40.9 nsec/% · km, whereas the pure length effect is 50.0 nsec/% · km. The difference is caused by the decreasing refractive index with increasing stress.[5]

The fast RLPD-data storage makes the method most suitable for observing dynamical processes, for example shrinkage of the (loose tube) jacketed fibres, and such measurements can be performed as accurately as 0.05‰ on an absolute scale by using the Fig. 2 curve-slope as a conversion factor from delay change to change of fibre length.

A typical RLPD-curve is shown in Fig. 6. At lower temperatures the fibre is in an unstressed mechanical state, i.e., the 38 psec/°C · km slope of the curve in that region represents internal physical properties of the doped glass material, only. In contrast, at higher temperatures, the variation of the light pulse propagation time through the fibre is mainly determined by the thermal expansion of the secondary coating material, the mechanical state of the fibre is stressed and a quite different line slope, 180 psec/°C · km, is observed. Also, the direct consequence of the measured shrinkage is seen in Fig. 6, namely a shift of the stress free temperature interval.

Theoretical Model of the Extrusion Process

The fibre length relative to the length of the plastic tube may be expressed in terms of the temperature T_n when of equal length. In a simple model this temperature T_n is expressed as

$$T_n = T_p - \left(\frac{\Delta \ell}{\ell}\right)_F \beta_p^{-1} - \zeta \beta_p^{-1}$$

where β_p is the thermal longitudinal expansion coefficent of the plastic and $\left(\frac{\Delta \ell}{\ell}\right)_F$ is the fibre elongation caused by the applied back tension force and where ζ is a geometrical factor taking into account the bending of the secondary coated fibre in the region where the fibre back tension is transferred to the plastic tube. T_p is the temperature of the plastic tube in said region, and a proper approximation to the formula above is to assume that T_p equals the temperature of the cooling water source which is located beyond the extruder head.

Disregarding the stress induced at some part of the fibre surface by the coiling of the fibre, the upper limit T_u of the temperature interval, where the fibre is not exposed to external longitudinal stress and which may be directly measured is given by the equation

$$T_u = T_n + 0.5 \varepsilon_F \beta_p^{-1}$$

where ε_F is the radius of curvature dependent free space for the fibre.[2]

Experiments and Discussion

Comparison between Optical and Mechanical Performance.

The table shows the values of the most important parameters. All of the fibres were 0.20 NA P_2O_5 - B_2O_3 - GeO_2 doped multimode fibres supplied with a 280 μm O.D. silicone primary buffer coating. In most of the experiments 88 μm O.D. glass fibres were used corresponding to half the cross sectional area of 125 μm fibres. The reason being to reduce the degree of mutual interaction between the plastic and the fibre at elevated temperatures. The inner and outer diameter of the polycarbonate plastic tubes were 0.8 and 1.4 mm, respectively.

TABLE OF EXPERIMENTS

Number of Experiment	Back Tension Force (newton)	Cooling Source Temperature (°C)	Fibre Diameter (μm)	Inner Diameter of Plast Tube (mm)	Fibre Length (m)	Measured Upper Limit of Stress-Free Temperature Interval(°C)	Measured Upper Limit Transformed to Coil Curvature: 100 mm
1	1.5	40	125	0.78	2800	30	40
2	1.25	60	88	0.75	620	25	31
3	1.25	20	88	0.78	780	7	14
4	2.0	40	88	0.78	500	-20	-14
5	1.25	40	88	0.77	845	10	16
6	0.5	40	88	0.77	660	39	45

The results of the experimental investigation of the Experiment 1 fibre is illustrated by Fig. 3. At temperatures below 30°C, the fibre is in an unstressed mechanical state as opposed to the temperature region above 30°C. During the measurements, the actual radius of curvature interval for said fibre was 110 mm to 150 mm implying a weighted average coil curvature R = 133 mm. Hence, by using the thermal coefficient of expansion of the plastic material 6×10^{-5}/°C, the lower limit T_L of the stress free interval, i.e., where the fibre starts to buckle, was calculated to be -32°C. Transformation to κ = 100 mm, which is typical in many cable constructions, gives a stress free temperature interval from -42°C to 41°C. Now assuming the acceptance of a 1‰ fibre elongation, which is realistic because this value is less than 1/4 of a typical proof test level, the long term operational temperature region is from -42°C to 66°, and this interval becomes significantly extended, whenever the secondary coated fibre is firmly fixed to a strain relief member characterized by a low thermal expansion coefficient.[4]

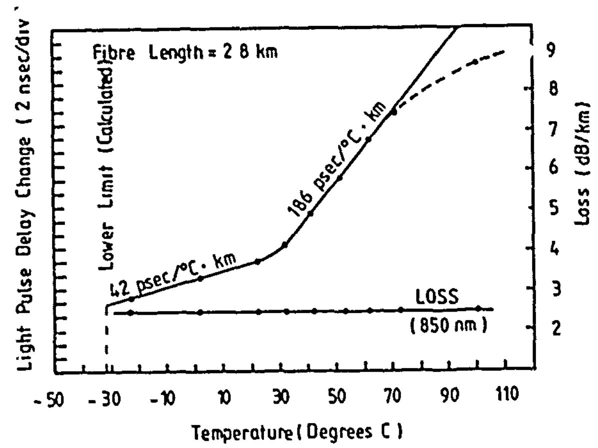

Fig. 3 Stress free and optical temperature intervals for a silicone coated multimode fibre in a loose polycarbonate tube
The full RLPD curve is the delay characteristics predicted by the theoretical model of the extrusion process - Coil curvature range: 110 mm to 150 mm - Note that the fibre might become significantly stressed without inducing additional loss (Exp. 1 - See Table of Experiments)

Also, the optical temperature interval of the same fibre was investigated, and the fibre loss versus temperature curve is shown in Fig. 3 as well. No loss increase was observed from - 25°C, which was the lowest measuring temperature, to 100°C, from which was concluded that the interval of no excess loss extends far above the temperature interval, where the fibre is stress free. The extremely

satisfactory temperature characteristics with respect to optical attenuation are mainly due to the buffer effect of the primary coating material and to a high degree of thermal stability of the secondary coating.

The two-mode curve, also shown in Fig. 3, is the RLPD-characteristics predicted by the model of the extrusion process which was discussed in the preceding paragraph. The smooth transition from the low to the high slope region around 30°C is due to the actual radius of curvature range 110-150 mm experienced by the fibre and which was also accounted for in the theoretical calculations. The theory compares most satisfactorily to the Experiment 1 data (below 70°C). This item is further discussed in the following sections.

The behavior of the experimentally obtained RLPD-curve above ~70°C is either due to a decreasing plastic stiffness, i.e., the Young modulus starts decreasing with an increase in temperature or due to a fast shrinkage occurring simultaneously with the fibre heating process.

Controlling the Fibre Excess Length

In the design of fibre optic cables with respect to temperature characteristics, it should be taken into account that the most suitable stress free temperature interval of the loose tube secondary coated fibre depends on

type of cable,

service environments,

cabling procedure,

accepted level of fibre elongation,

and

specifications in general.

Hence, it is most important to be able to control the fibre excess length in the loose plastic tube. In Fig. 4, it is illustrated that the upper limit T_u of the temperature interval, where the fibre is not exposed to external longitudinal stress, can be adjusted in almost perfect agreement with the proposed theoretical model of the extrusion process. The back tension force applied to the fibre was changed, and the cooling water temperature was fixed at 40°C in the experiments shown in Fig. 4. The negligible two degrees systematical deviation observed is explained by the approximation introduced in the paragraph dealing with the model of the extrusion process. The fibre remains some time in ~30° C air before the transfer of the back tension force takes place, and therefore some further cooling or heating occurs in this region: For cooling water temperatures in excess of ~30°C, T_p will be lower than the water temperature, and the approximation will give too high a value of T_u. In contrast, cooling water temperatures below the environmental temperature will imply that the theory predicts too low T_u values. The more pronounced effect of the approximation is seen by Fig. 5.

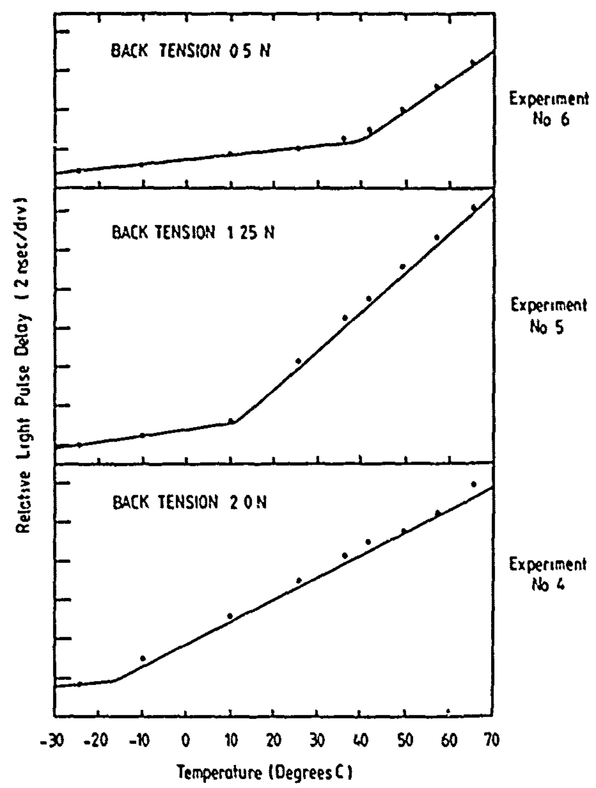

Fig. 4 Controlling the fibre excess length in the loose polycarbonate tube by changing the back tension force for fixed cooling source temperature
The full curves are the delay characteristics predicted by the theoretical model of the extrusion process

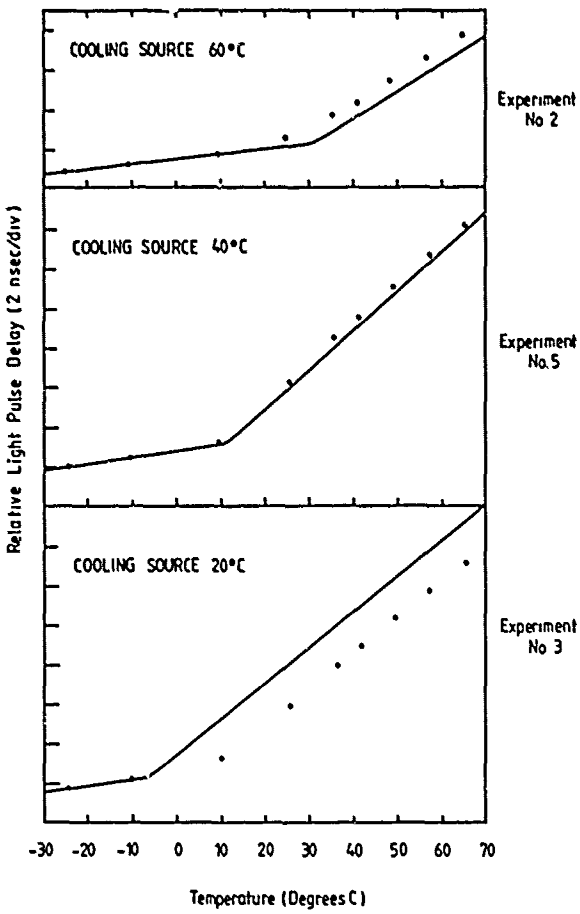

Fig. 5 Controlling the fibre excess length by changing the temperature of the cooling source for fixed back tension force
The data are given in the Table of Experiments - The full curves are the predictions of the theoretical model which seems to overestimate the effect of the cooling source - See text

Shrinkage

It has been concluded that it is possible by a uniform well controlled extrusion process to adjust the fibre length relative to the length of the plastic tube in agreement with a theoretical model. Obviously, it is of primary importance to know whether this length ratio does change with time and if so, to find the cause for the change.

Because such dynamical relaxation phenomenons are primarily expected to take place at higher temperatures, thermal stability of loose tube polycarbonate jacketed optical fibres were investigated at elevated temperatures.

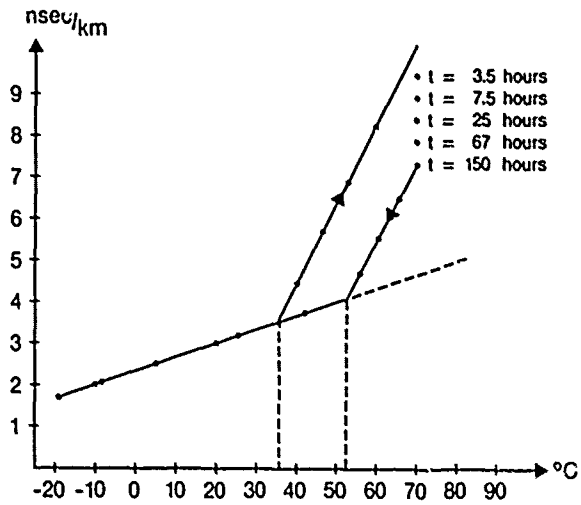

Fig. 6 RLPD measurement before, during, and after shrinkage
The stress free temperature interval is shifted to the right by the recorded dynamical relaxation

Fig. 6 summarizes the result of a RLPD-measurement before, during, and after shrinkage. The measurements were performed from -20°C to 70°C, and when 70°C were reached, the fibre was exposed to this temperature for 150 hours. After this procedure, as it is also shown in Fig. 6, the stress free temperature interval was measured again and a ~17°C increase of the upper limit of the interval induced by the 0.73% shrinkage was observed. To investigate the dependence of the shrinkage process on the level of compressive strain experienced by the plastic tube (due to the fibre elongation), a series of 3 experiments was carried out at 71°C, each of these characterized by a specific level of fibre excess length in the plastic tube.

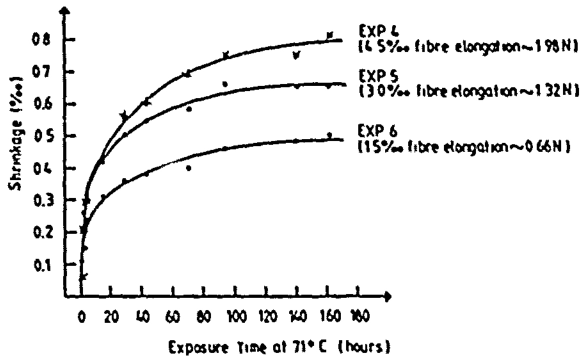

Fig. 7 Dynamical relaxation characteristics for loose tube polycarbonate secondary coated optical fibres at 71°C
The degree of the irreversible dynamical relaxation depends strongly upon the level of compressive strain experienced by the plastic tube

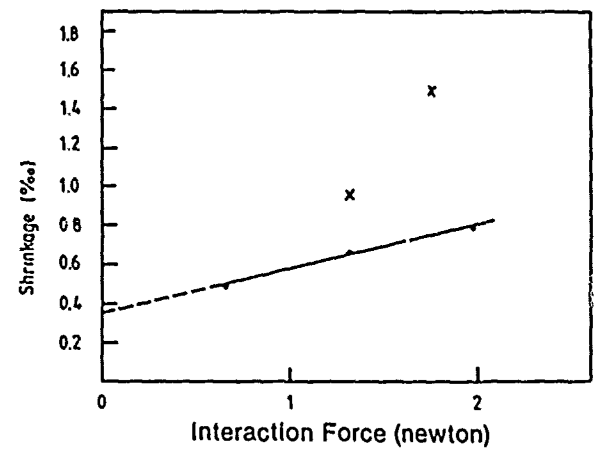

Fig. 8 Shrinkage after 160 hours exposure at 71°C (•) and at 92°C (x) as a function of mutual interaction forces between the glass fibre and the plastic tube material

The results are shown in Fig. 7. The lower of the curves refers to a fibre elongation of 1.5‰ at 71°C, the medium curve to a 3.0‰ elongation at 71°C, and the upper curve to a 4.5‰ elongation, also at 71°C. The equivalent forces are 0.66 N, 1.32 N, and 1.98 N, respectively. The cross section area of the tubes are approximately 1 mm^2. The shrinkage process depends strongly upon the level of compressive strain experienced by the plastic tube induced by the fibre elongation. In Fig. 8, the shrinkage after 160 hours exposure at 71°C is plotted against the actual compressive force acting at the process. The figure indicates a linear relationship and extrapolation to zero compressive strain results in a shrinkage value as low as 0.35‰ after the 160 hours exposure to 71°C as compared to 0.49‰ at 0.66 N, 0.66‰ at 1.32 N, and 0.79‰ at 1.98 N. Even at very high compressive strain values, the observed shrinkage is as low as 0.8‰; hence, the conclusion that polycarbonate exhibits extremely good thermal stability at 70°C.

A similar investigation has been performed at 92°C, and the results are shown in Fig. 9. Here, a faster and larger shrinkage was observed, and also the dependence on the mutual stress interaction force acting between the glass fibre and the plastic tube is more pronounced. However, the shrinkage values obtained at 92°C might be somewhat overestimated because they are based upon a linear RLPD-curve from T_u to 92°C as it is illustrated by Fig. 3, and it has not been firmly ascertained whether the curved nature of the RLPD-characteristics at temperatures above ~70°C are due to a decreasing Young modulus or to a fast shrinkage occurring simultaneously with the heating process. A remeasurement of the RLPD-curves could give a good deal of information on said problem depending upon whether the thermal expansion coefficient remains unchanged during the relaxation process.

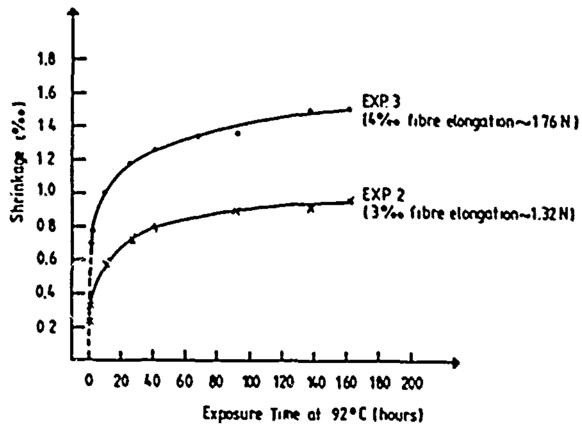

Fig. 9 Shrinkage of loose tube polycarbonate secondary coated fibres at 92°C
The degree of the irreversible dynamical relaxation depends strongly upon the level of compressive strain experienced by the plastic tube

Anyhow, also at 92°C polycarbonate secondary jacketed optical fibres show excellent thermal stability. Even at a compressive strain as high as 1.34 N, the shrinkage is only 1‰ for a 160 hours exposure, and for the practical purposes, i.e., much lower mutual interaction forces, the shrinkage is expected to be much less, see Fig. 8.

Conclusion

Thermal properties of loose tube polycarbonate secondary coated optical fibres with regard to optical and mechanical performance have been discussed. It has turned out that the fibre length relative to the length of the plastic tube can be accurately measured by obtaining the light propagation time versus temperature characteristics. This is due to a factor 5 slope increase from the region where the fibre is free to move to the region where it becomes stressed by the thermal expansion of the plastic tube.

It was observed that the temperature interval with no excess loss could be much broader than the temperature interval where the fibre is not elongated by the expansion of the plastic secondary coating with the inference that it is much more important to control the stress free temperature interval as opposed to the interval of no excess loss. In fact, it has been observed that the upper limit of the temperature interval, where the fibre is not exposed to longitudinal stress, can be well controlled over a wide range by adjusting different parameters in almost quantitative agreement with a model of the extrusion process.

Finally, the change of the stress free temperature interval with time has been investigated at 71°C and at 92°C. The observed irreversible dynamical relaxation or the shrinkage of the plastic tubes depend upon the level of compressive strain experienced by the secondary coating material. For compressive strain forces corresponding to less than a 1.5‰ elongation of a 125μm optical fibre, i.e., a practical relevant situation, the shrinkage would be less than 0.6‰ for a 160 hours exposure at 70°C and less than 1‰ for a 160 hours exposure at 90°C.

Hence, loose tube optical fibres with silicone primary coating and polycarbonate secondary coating show excellent optical and mechanical temperature characteristics.

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